

TITLE OF INVENTION

MEANS AND METHOD OF DATA ENCODING AND COMMUNICATION AT RATES ABOVE THE CHANNEL BANDWIDTH

BACKGROUND OF THE INVENTION

5 Technical Field

The present invention relates to the communication of signals, in particular, to the transmission and reception of digital signals. More specifically, the present invention relates to encoding and decoding the data being sent to reduce the offset of the signal around the sampling threshold voltage when the data rate is above the
10 bandwidth of the channel.

The present invention is particularly applicable to interfaces between integrated circuits and for high speed communications, such as currently addressed by Asynchronous Transfer Mode (ATM), Gigabit Ethernet, 3GIO, RapidIO, Hyperchannel and Fibre Transmission Channels, and makes possible yet higher data
15 rates for a particular bandwidth of the transmission medium.

Background of the Invention

As the operating frequency of complex digital communication and data transfer systems increases, one of major technical challenge has been to improve the data transmission when the data rate is about or exceeds the bandwidth of a
20 communication channel. A conventional communication channel comprising a differential driver, such as an LVDS (Low Voltage Differential Signaling) driver, a production package for the integrated circuit such as a BGA (Ball Grid Array), a printed circuit board, a receiver packaged similarly with its ESD (Electronic Static Discharge) structure, acts together as a filter. In the example given of a LVDS driver,
25 BGA, pcb trace, BGA and receiver ESD structure and input parasitics, will have a cut-off frequency of around 1GHz, and with between 4 and 6 poles, the slope will be sharp. A signal at 6GHz (or 12Gbps) may only have 20% of the amplitude of a signal at 1GHz (2Gbps). A 20GHz (40Gbps) signal over a 2GHz BW channel may have only 10% of the amplitude of the 2GHz (4Gbps) components.

The receiver commonly has a relatively fixed sampling threshold voltage or current. If the signal being transmitted is a sine wave, and small changes are introduced at the time the sine wave is transmitted, such as by channel calibration processes or simply jitter, the entire signal can shift such that none of the data points for a period after the time shift cross the sampling threshold. An example of this is shown in Fig. 2. In this plot, the signal at 6GHz is sent through a channel with 1GHz bandwidth, and then at the start of the third cycle, the data is shifted in the transmitter by 5ps. The result is that at the receiver, the signal no longer crosses the threshold. This problem is related to the ratio of the bandwidth of the channel to the bandwidth of the data, and the degree of non-linearity in the channel, so a 12Gbps signal sent over a channel with 1GHz bandwidth will behave as shown in Fig. 2, but 40Gbps over a 2GHz BW channel would have much worse behaviour.

The problem gets even more complex when the signal is not an almost continuous sine wave but rather a data signal, such as in Fig.3, in which the same 1GHz bandwidth channel is shown, sending data which varies in bandwidth from 1GHz to 6GHz. A channel implemented using standard production packages, such as BGAs, 1GHz bandwidth drivers and with the receiver having the normal 2KV HBM (Human Body Model) ESD protection, will cause signals above 1GHz to have a dramatic loss in amplitude. It is normal practice in such situations to equalise the channel by attenuating the lower frequencies, effectively increasing the channel bandwidth. However, the tolerance on the components in the channel and the number of poles, typically 4 to 6 even in a direct chip to chip link, limits greatly the practical use of equalisation. The result is that the system must tolerate the filter response when sending data.

The limited ability to equalise the channel at a practical level means that above the pass band of the channel, the data will be attenuated. This attenuation can be managed using tracking receiver thresholds, however, the impulse response of the filter causes a more dramatic problem: the entire data signal shifts over a small number of cycles as a function of tiny amounts of phase noise or phase variations.

In a channel with 1GHz bandwidth (BW), if the signal comprises a pattern at 1GHz, then the driver and receiver will reach their saturated values. When the data pattern changes from a 1GHz repetitive signal to a series of data bits equivalent to a 6GHz repetitive signal, the speed of response depends on where in the sine wave the 1GHz signals happens to be at the point of change. Each cycle of the 6GHz signal represents a little over 1 radian of the 1GHz signal. The 1GHz signal normalised to +/- 1V, will change at a rate of 2V per nS over the radian centred on the sampling threshold, but less than 1/12th of this over 1 radian of the cycle centred about the apex of the 1GHz sinusoid. For the reader unfamiliar with Kalman filtering and signal processing, the received signal can be considered to have a momentum, determined by the impulse response of the channel filter characteristic. This means that a 1 unit time delay of the signal, imposed on the signal as it crosses the sampling threshold, will have 6 to 12 times the effect at the receiver than the same unit time delay of the signal as it is at its apex, where the unit of time is a very small number.

The variation in time in the received signal, caused by a delay imposed on the signal before the driver, can vary over a ratio of 1:6 in the example given above. The actual variation is a product of the two bandwidths: the bandwidth of the channel, and the bandwidth of the data. This problem is evident from Fig. 3, where a change from DC to 1/8th cycle of a 1GHz signal, to a 6GHz signal occurs in rapid succession in a channel with a 1GHz bandwidth.

The use of transmission codes to improve the received characteristics of the information is well known in the prior art. For example, Manchester and 8b/10b encoding is commonly used to ensure there are sufficient transitions present in the bit stream to make clock recovery possible, as in US 4,420,234 and US 4,486,739. Coding is known also as a means to improve noise immunity of a signal in a communication channel, such as described in US 5,944,842. Other coding methods have been used for many decades to increase the probability of detecting single or multiple bit errors. However, these existing schemes operate within the channel bandwidth, or within the bandwidth that can support baseband transmission and sampling using a relatively fixed sample threshold voltage or current.

BRIEF SUMMARY OF THE INVENTION

The present invention applies a coding to reduce the pattern dependent artifacts within a communication channel, that result from the channel bandwidth
5 being less than the data rate.

It is an object of the present invention to enable channel calibration or perform an adjustment by the introduction of small timing increments and decrements reliably when the data is sampled by a relatively fixed threshold as described in PCT/RU01/00482, PCT/RU01/00365, GB 0131100.0 but the channel bandwidth is
10 insufficient.

Another object of the invention is to increase the maximum amount of data that can be communicated across a channel, in the case where the transmitter and receiver can operate at a frequency well above the bandwidth of the transmission medium but the transform or filter function imposed by the transmission medium
15 distorts the signal such that it cannot be sampled reliably.

It is another object of the invention to reduce the artifacts introduced into the signal from the limited and non-linear characteristics of the channel, such as by reflections not being absorbed efficiently due to the frequency of the reflection being in the non-linear region of the line termination components.

It is still another object of the invention to reduce the offset of the data from the sampling threshold that occurs as a function of the data pattern when the data rate
20 exceeds the bandwidth of the channel.

It is another object of the invention to fold the requirements for a DC balance or for a certain number of signal changes per data word into a single code that achieves
25 these goals simultaneously with improving the data rate.

In accordance with these and other objects, the present invention is a coding means for coding data represented by input symbols into codes for transmitting the codes by a transmitter along a communication channel, the codes being represented in the channel by signals having a limited minimum and maximum pulse width, to
30 enable sampling the coded data at a receiver at each receiver's clock period, wherein

the input symbols are encoded to have the minimum signal pulse width longer than one period of the receiver's sampling clock.

Preferably, the input symbols are encoded to have a minimum signal pulse width approximately defined by formula

$$P_{\min} = \frac{1}{2\tau} F, \text{ where } \tau \text{ is a minimum bit interval}$$

providing a required bit error rate (BER) of data, the bit interval being a period of time required for the transfer of one bit of information, and F is the bandwidth of the channel. The required bit error rate of data is defined by a specialist in the art taking into account various parameters of a communication channel, such as timing uncertainty of a signal, noise in the channel, metastability in the receiver, etc.

Various approaches known in the field may be used by a specialist in the art to estimate minimal bit interval providing the required BER, which can vary greatly, say, from 1 to 10 values of RMS jitter in the channel. The more strict are requirements to the quality of data transfer, the longer shall be the bit interval. And similarly, the more strict are requirements, the lower is the data rate providing the required BER in the channel. As mentioned above, according to the invention, the input symbols are coded to have the minimum signal pulse width longer than one period of the receiver's sampling clock.

For example, if the bandwidth of the channel is 3 GHz and τ is 80 picoseconds, P_{\min} will amount to $1/2 \times 3 \times 10^9 \times 80 \times 10^{-12} \sim 2,08$, thus, for this case, the input symbols will be preferably encoded to have a minimum signal pulse width P_{\min} which is at least twice as long as one period of the receiver's sampling clock, or in other terms, the minimal signal pulse width will be equal to 2 bit intervals, as illustrated in Fig.5.

A coding means can be described by means of a code table wherein each input symbols is assigned one or more, in the present application, two codes, when a DC balance is required. According to the invention, the code table may be created taking into account various constraints selected from maximum and minimum pulse widths (see Fig.2), a code word width and DC balance requirement of the signal in the channel.

According to a first embodiment of the invention, 8 bit input symbols are encoded into a 13 bit output codes in accordance with the code table provided that, in a sequence of two codes, each bit, except for the first and the last bit of the sequence, must have the same left or right neighbor bit. According to a second embodiment, 8 bit input symbols are encoded into 16 bit output codes in accordance with a code table which is created to produce a DC balanced signal and containing two parts of codes, one part for coding symbols with negative current disparity, and another part for coding symbols with positive current disparity, the table being such that:

- 10 each input symbol corresponds to two codes, one code being from the first part of the table and the second code being from the second part;
 codes presented in both parts of the table shall be assigned to the same input symbol;
 within each code presented in the part of the table for negative current disparity, the sum of "1"s is equal to 8 or 9;
- 15 within each code presented in the part of the table for positive current disparity, the sum of "1"s is equal to 7 or 8;
 the current disparity is negative when the previous code has 9 or 8 "1"s; and the previous state of disparity was negative, otherwise it is positive;
- 20 in any sequence of two codes, one code consisting of 8 "1"s and taken from one part of the table, and another one being any code taken from the same part of the table, each bit of the sequence must have the same left or right neighbor, except for the first and the last bit of the sequence;
 in any sequence of two codes, one code consisting of the number of "1"s different from 8 and taken from one part of the table and another code being any one taken from the other part of the table, each bit of the sequence must have the same left or right neighbor, except for the first and the last bit of the sequence;
- 25 the two parts of the table contain preferably equal number of codes.
- 30 The code table may be reordered to provide the optimal coder implementation such as having minimal logical terms. For example, a modification of the table of the

first embodiment gives a fast and elegant means to enable 8 bit input symbols encoding into 13 bit output codes. In this case, the constraints include: minimal pulse width is 2, maximal pulse width is 16, code word width is 13. An implementation of the coder/decoder means for a table corresponding to these requirements can be
 5 implemented as presented in Appendix A.

Further improvement of the coder/decoder implementation can be achieved by codes reordering such that: codes are splitted into two groups with 256 codes in one group and 14 codes in the second group, wherein the codes of the first group are nonsymmetrical, while the codes of the second group are symmetrical. The first group
 10 of the 256 codes can be splitted into two groups of 128 codes each, such that the center, 6th, bit is "0", while in the second group the central bit is "1".

Further, for each code of the first group there is a complementary code of the second group. Such a symmetry provides the central bit to be assigned to one of input symbol bits.

15 Further, each subgroup may be subdivided into two smaller groups each of 64 codes, such that the first group will comprise codes having a number built from bits from 12th to 7th bits is less than the number built from bits from 5th to 0 bits.

In each new subgroup, for each code of the first group there is a code of the second group with a reversed bit order. Such a symmetry provides the way to reduce
 20 the size of amorphous table and simplify the decoder.

Finally, the codes may be ordered in these small subgroups to simplify the logic functions they describe.

Thus, the coder and decoder may be implemented much more efficiently, as shown in appendices D and E.

25 In still one more aspect of the invention, a communication apparatus is provided comprising a transmitter, a receiver, and a coding means according to the first aspect of the invention.

According to a preferred example embodiment of the communication apparatus, the coding means produces a code wherein the minimal signal pulse width
 30 is equal to 2 bit intervals, while the receiver takes multiple samples during each clock

period to track the dynamic variation in the temporal or amplitude thresholds of the data to improve the overall coding efficiency.

To achieve this, a receiver for high speed interconnect may be used as described in GB 0131100.0 filed on 31 December 2002 claiming priority from US 5 60/317,216 filed on 6 September 2001, the whole description of which application being incorporated herein by reference. The receiver comprises at least one sampler for sampling data, for providing a series of signal copies, each signal copy having a Bit Error Rate Distribution, and a means to combine the signal copies so as to produce a combined signal having the Bit Error Rate Distribution narrower than the 10 distribution of a single signal copy. Further, according to this embodiment, the samples taken by the receiver may be spread in time around a regular sampling clock that enables the dynamic shift in the received data to be tracked by matching shifts in the sampling clock or inverse shifts in delay circuitry within the receiver. A coding means of the invention may be further supplemented by a decoding means to further 15 decode the codes into respective output symbols.

A coding means as well as the decoding means can be implemented in hardware, such as a hub, switch, router, modem or processor, as well as in a logic element synthesised or created based on a table listing of the code alphabet. Alternatively, the coding or decoding means may be implemented in a lookup table.

20 The code table may be splitted into subtables and an intermediate code may be computed from which the final code is determined.

In another aspect of the invention, a method of coding data represented by input symbols into codes for transmitting along a communication channel is provided using the coding means of the first aspect of the invention.

25 In still another aspect of the invention, a method of communication including coding data represented by input symbols into codes, transmitting the codes along a communication channel, and receiving data, wherein the data are coded using a method of coding of the present invention.

30 Further, a method of decoding codes into respective output symbols is provided.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

For a better understanding of the present invention and the advantages thereof and to show how the same may be carried into effect, reference will now be made, by way of example, without loss of generality, to the following description now taken in conjunction with the accompanying drawings in which:

Fig.1 shows a general block diagram of the communication channel employing the coding means according to the present invention.

Fig.2 shows a waveform for a signal received in a 1GHz BW channel, with a 5ps time delay introduced into the 6GHz transmitted signal at the start of the third cycle.

Fig.3 shows a waveform for a signal received in a 1GHz BW channel, where the transmitted data has rapid transitions from DC to $1/8^{\text{th}}$ cycle of 1GHz to 6GHz tone.

Fig.4 shows partially an eye diagram for a typical communication channel.

Fig 5. illustrates values of the minimal and maximal pulse width.

Reference will also be made to the following appendices:

Appendix A is a description of a preferred embodiment of Fig. 1 in the Verilog Hardware Description Language, from which actual circuitry can be synthesised using widely used CAD tools such as Ambit from Cadence, and which can be understood easily by a person skilled in the art of modern and high speed VLSI design, including a preferred code table for encoding data of 8 bits in length.

Appendix B is an example of a computer program in the C++ language for generating the code tables or alphabet as required by the present invention.

Appendix C is an alphabet of the code table for a coding scheme as described by the present invention and in which the code is DC balanced for coding an 8 bit data word such that the minimum pulse width is two sample periods, the maximum pulse width is 9 bits and the code is DC balanced.

The code is presented in a table having two parts, the first being a negative disparity table, and the second a positive disparity table. After each word the current

disparity is calculated in the same manner as for existing 8b/10b coders, such that if the code contains less than half 1s then the disparity after this becomes negative, if it has more 1s than half the code width then the disparity becomes positive. If the number of ones is equal to the number of zeros then disparity remains the same as in the previous cycle. The state of the disparity determines from which part of the table the symbol should be taken. The order of codes can be changed, however, codes presented in both parts of the table should preferably be assigned to the same symbol to simplify decoding.

Appendix D is a description of a preferred embodiment of an 8 bit data word coding into 13 bit codes as described by the present invention, in which the minimum pulse width is two sample periods, the maximum pulse width is 16 bits, code words width is 13. An implementation of the decoder means for this coder is presented in Appendix E.

DETAILED DESCRIPTION OF THE INVENTION

In contemporary communication channels, the data can be viewed in an eye diagram, such as in Fig. 4. In this diagram the data moves from sample point to sample point, with changes in signal polarity at a point equidistant to the centre of the eyes of each sampling point. In the examples given earlier, this amounts to sending 6GHz of data down a channel with 1GHz bandwidth (BW).

The present invention reduces the pattern dependent shift of the data in each eye by coding the data to move from eye to eye such that instead of having the opportunity to change polarity between each eye, it must stay in a state for a given number of eyes, such as 2. The number of eyes is not reduced.

A detailed description of the invention will now be given, with reference to Fig.1 illustrating a communication system in which an input data word 2 is encoded by encoder 1 to have special characteristics as described later, the encoded data is then presented to transmitter 3, sent through communication channel 5 into receiver 7, then decoded in decoder 4 to produce a replica of the original data at output 11. In this system the transmitter and receiver can operate at higher sample or clock rates

than the incoming data rate, but that data rate is still well above the bandwidth of channel 5.

The encoder 1 according to the present invention encodes the data 2 to use optimally the sampling rates available in the transmitter and receiver. Hitherto, if data is sent at a rate much higher than the channel bandwidth, for example at 6 times the channel bandwidth, then the impulse function of the channel causes the received signal to be offset and distorted such that it cannot be received reliably using a fixed threshold receiver. The function of the encoding means is to reduce the effect of the impulse or filtering function of the channel.

An example of a suitable encoder is given in Appendix D in the form of a hardware description in the Verilog language, from which a working encoder can be synthesised automatically using widely available CAD tools.

An example of a suitable decoder is given in Appendix E in the form of a hardware description in the Verilog language, from which a working decoder can be synthesised automatically using widely available CAD tools.

The first step in applying the present invention is to determine the requirements of the receiver, in particular, whether the code it requires must be DC balanced or not, and how many bit intervals, or clock cycles, can elapse without the signal changing, that is, the lower frequency limit, or the minimum number of transitions, of the received data. Means for doing this type of coding is well understood and widely used.

The next step, novel to the present invention, is to determine the ratio of the maximum data bandwidth that can be sent through the channel as a continuous repetitive tone, to the maximum data rate that can be supported by the channel given maximum irregularity in the data. For a channel, which can transmit a 6.5GHz tone, a typical maximum data rate for data containing step changes is 3.25GHz, a 2:1 ratio. This means that the data must remain constant for two sample periods, i.e. for two bit intervals, whenever it changes. This is distinct and different from simply sending the data at half the data rate: the data even at 3.25GHz will have encoding, such as 8b/10b, so the useful data will be 20% lower than this, or 2.6GHz of useful data

(either 2.6Gbps or 5.2Gbps depending on whether the data is clocked on one edge only or on both edges). Moreover, the coding scheme that is described here uses all the eye transition points, so it uses the maximum capacity of the channel given these criteria.

- 5 Once the criteria are identified, the algorithm as embodied in the C++ program and the numerous obvious derivatives of this program to cover other code requirements, searches for the minimum code length that meets all the criteria, and then searches for the maximum alphabet for that code length and code constraints.

10 For example, consider a channel where the minimum signal pulse width is two sample periods, or two bit intervals, and the minimum number of transitions of the signal is one per 16 bits.

15 The program in Appendix B can be used to find the code table, as reproduced in Appendix A. This particular table is preferred because it is the smallest table meeting these two requirements. This takes 8 bits of incoming data and expands it to 13 bits, which can be transmitted reliably through the 1GHz BW channel under the conditions described above, namely where the receiver, channel compensation and calibration enables 3.25GHz to be transmitted. In this case, if the data is clocked on both edges, then the data capacity without coding is 7Gbps, which is 5.6Gbps of useful data assuming that 8b/10b coding is used in the original channel. If the same data is applied to the 8b/13b coding scheme in Appendix A, then 8Gbps of real data is transmitted, a 43% increase in the real data conveyed by the channel.

25 If the requirement is added that the code be DC balanced, then the minimum code is probably that shown in Appendix C, which is a 8b/16b code, namely 8 bits of real data is expanded to be 16 bits. This code is used by selecting 256 of the letters or entries to act as a 8b/16b code, using parity and disparity to select sequential code tables for sequential words in the same way as an 8b/10b coder. The 8b/16b alphabet is 319 code words in length. In this case, compared to the channel which transmitted 7Gbps using 8b/10b encoding, the channel with 8b/16b coding can now send 6.5Gbps of real data instead of 5.6Gbps, an increase of 16%. In computing the code alphabets, the number of codes must be greater than two raised to the power of

30

the number of bits to be sent in the original data word. In the case of the 8b/13b coding scheme, there are 269 codes in the alphabet, which is more than 256. The figure 256 is the two raised to the power of data word size, 8 bits. The code has a maximum interval between transitions of 9 bits.

5 Where the maximum interval between clock changes is increased, the efficiency of the coding system also increases. For example, if a clock transition is only required every 1024, then the number of codes rejected is a much smaller proportion to the possible alphabet than in the case with small words. This increases the maximum data rate even further.

10 It can be seen clearly from the two example code tables, that increasing the number of constraints or requirements for the code reduces its efficiency. Three bits are lost in an 8 bit coding scheme simply by adding the requirement that the code is DC balanced. A preferred embodiment thus minimises the number of constraints applied to the code word, except that the code word shall have a minimum pulse
15 width which is more than one clock period.

 A method for increasing the interval between clock changes is to apply the sampling scheme as described in US 60/317,216 of 06.09.2001 by the present inventors, in which a plurality of samples are made and the difference across these samples is used to track the data. The means to track the voltage and time threshold
20 of the received data, in essence by taking a number of samples and then determining which sample is the centre of the sampling eye, can be used to greatly increase the interval in which no transitions are required. In an advanced preferred embodiment of the present invention, these two techniques are combined to create longer code words, thus greater coding efficiency, and enable these long code words to operate
25 reliably.

 An alternative to computing the code in a single table lookup, or logic synthesised from the description of such tables, is to split the table into sections, such as in two sections and to compute logic value, such as a disparity value, and use this value to generate the final code in conjunction with the intermediate results from the
30 smaller tables.

Where the code table is computed such as by using a program such as that in Appendix B, but the length of the alphabet is short of the required length, the list of rejected codes can be re-examined to determine if sufficient increase in the alphabet length can be achieved by linking two code words. That is, an alphabet is used to
 5 generate the first code word, then a flag or carry value is used to index a further code table such that the code applied to the subsequent data word is from a different alphabet to that used to encode the first word.

Once the code table has been generated, it is preferred to validate the table by running all possible variations of two adjacent input data words through the coder,
 10 through an extreme worst case HSPICE model of the driver, package with parasitics, pcb, any connectors including the via or connect hole model in the pcb, receiver package with parasitics, receiver ESD structure and receiver buffer, and then into the decoder. The encoder and decoder in this validation process is implemented preferably in a HDL, such as using the Verilog or VHDL languages, and confirm that
 15 the entire table meets the required objectives. This has been done for the code tables published here.

It is possible to use the above validation process to extend the length of an alphabet, by accepting code words that can validate but do not meet the design criteria. This is a method of generating the alphabet but is not preferred because
 20 variations in parasitics in the channel, and channel noise, can cause irregular and non-linear behaviour which will affect such alphabets very much more adversely than for alphabets which are developed using a program such as shown in Appendix B that are correct by construction.

Whilst the example embodiments have focused on a coder, it is obvious from
 25 their description and the Appendices, that the decoder is simply the inverse operation and the construction of this decoder, once the coder has been defined, is evident to anyone skilled in the art of digital system design.

The present invention solves a particular problem in a communication system where the transmitter and receiver can operate reliably at frequencies well above the
 30 bandwidth of the channel. The design of such systems is very complex and highly

specialised, requiring the solution of a multitude of problems. Once that design solution is in place, the present invention allocates part of the performance of the transmitter and receiver to codes which apply some of the bandwidth of the transmitted data for overcoming bandwidth deficiencies in the channel medium and interconnect. The present invention thus reduces the total number of real data bits that are received, compared with a channel which simply sends the data and samples it at the receiver. However, given that a transmitter and receiver with the required performance can be designed and implemented as is now the case with contemporary activities, the present invention allows more real data to be communicated in the case where the sampling rate exceeds the channel bandwidth by a multiple of two or more.

Hardware Description in the Verilog language of a coder for coding data with minimum pulse width of 2 sample periods and a maximum period between transitions of 16 sample periods.

```

module coder_8B13B(
    clock,          // clock
    reset,          // power up reset
    din,            // Data in
    cin,            // Command in
    out);           // data output

    input          clock;
    input          reset;          // system reset. Active high
    input [7:0]    din;            // {H,G,F,E,D,C,B,A}
    input          cin;            // 1 - Command, 0 - data
    output [12:0] out;             // {m,l,k,j,h,g,f,i,e,d,c,b,a}

    //-----
    // internal signals:
    //-----

    reg [12:0] d;

    //-----
    // code:
    //-----

    always @(posedge clock or posedge reset) if (reset) begin
        d <= 13'b00000001100011; // code for data 0
    end
    else begin
        if (cin) begin            // Commands encoding
            case ({din[7:0]})
                8'h1C : begin d <= 13'b001111000000000; end
                8'h3C : begin d <= 13'b111111100111111; end
                8'h5C : begin d <= 13'b110001111111111; end
                8'h7C : begin d <= 13'b11111110000000; end
                8'h9C : begin d <= 13'b111001111111111; end
                8'hBC : begin d <= 13'b1111111000011; end
                8'hDC : begin d <= 13'b11111000000000; end
                8'hFC : begin d <= 13'b1111111000111; end
                8'hF7 : begin d <= 13'b1111111001111; end
                8'hFB : begin d <= 13'b1111111001100; end
                8'hFD : begin d <= 13'b1111111100000; end
                8'hFE : begin d <= 13'b1111111100011; end
                8'hFF : begin d <= 13'b1111111100111; end
            endcase
            // command FF by default
        end
    end
end

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        default : begin d <= 13'b1111111100111; end
    endcase
end
else begin                                     // data encoding
5    case ({din[7:0]})
        8'h00 : begin d <= 13'b00000001100011; end
        8'h01 : begin d <= 13'b00000001100111; end
        8'h02 : begin d <= 13'b00000001110000; end
        8'h03 : begin d <= 13'b00000001110011; end
10       8'h04 : begin d <= 13'b00000001111000; end
        8'h05 : begin d <= 13'b00000001111100; end
        8'h06 : begin d <= 13'b00000011000000; end
        8'h07 : begin d <= 13'b00000011000011; end
        8'h08 : begin d <= 13'b00000011000111; end
15       8'h09 : begin d <= 13'b00000011001100; end
        8'h0A : begin d <= 13'b00000011001111; end
        8'h0B : begin d <= 13'b00000011100000; end
        8'h0C : begin d <= 13'b00000011100011; end
        8'h0D : begin d <= 13'b00000011100111; end
20       8'h0E : begin d <= 13'b00000011110000; end
        8'h0F : begin d <= 13'b00000011110011; end
        8'h10 : begin d <= 13'b00000011111000; end
        8'h11 : begin d <= 13'b00000011111100; end
        8'h12 : begin d <= 13'b00000110000011; end
25       8'h13 : begin d <= 13'b00000110000111; end
        8'h14 : begin d <= 13'b00000110001100; end
        8'h15 : begin d <= 13'b00000110001111; end
        8'h16 : begin d <= 13'b00000110011000; end
        8'h17 : begin d <= 13'b00000110011100; end
30       8'h18 : begin d <= 13'b00000110011111; end
        8'h19 : begin d <= 13'b00000111000000; end
        8'h1A : begin d <= 13'b00000111000011; end
        8'h1B : begin d <= 13'b00000111000111; end
        8'h1C : begin d <= 13'b00000111001100; end
35       8'h1D : begin d <= 13'b00000111001111; end
        8'h1E : begin d <= 13'b00000111100000; end
        8'h1F : begin d <= 13'b00000111100011; end
        8'h20 : begin d <= 13'b00000111100111; end
        8'h21 : begin d <= 13'b00000111110000; end
40       8'h22 : begin d <= 13'b00000111110011; end
        8'h23 : begin d <= 13'b00000111111000; end
        8'h24 : begin d <= 13'b00000111111100; end
        8'h25 : begin d <= 13'b00011000000011; end
        8'h26 : begin d <= 13'b00011000000111; end
45       8'h27 : begin d <= 13'b0001100001100; end
        8'h28 : begin d <= 13'b0001100001111; end
        8'h29 : begin d <= 13'b0001100011000; end
        8'h2A : begin d <= 13'b0001100011100; end
        8'h2B : begin d <= 13'b0001100011111; end
50       8'h2C : begin d <= 13'b0001100110000; end
        8'h2D : begin d <= 13'b0001100110011; end

```

```

5      8'h2E : begin d <= 13'b0001100111000; end
      8'h2F : begin d <= 13'b0001100111100; end
      8'h30 : begin d <= 13'b0001100111111; end
      8'h31 : begin d <= 13'b0001110000011; end
      8'h32 : begin d <= 13'b0001110000111; end
      8'h33 : begin d <= 13'b0001110001100; end
      8'h34 : begin d <= 13'b0001110001111; end
      8'h35 : begin d <= 13'b0001110011000; end
      8'h36 : begin d <= 13'b0001110011100; end
10     8'h37 : begin d <= 13'b0001110011111; end
      8'h38 : begin d <= 13'b0001111000000; end
      8'h39 : begin d <= 13'b0001111000011; end
      8'h3A : begin d <= 13'b0001111000111; end
      8'h3B : begin d <= 13'b0001111001100; end
15     8'h3C : begin d <= 13'b0001111001111; end
      8'h3D : begin d <= 13'b0001111100000; end
      8'h3E : begin d <= 13'b0001111100011; end
      8'h3F : begin d <= 13'b0001111100111; end
      8'h40 : begin d <= 13'b0001111110000; end
20     8'h41 : begin d <= 13'b0001111110011; end
      8'h42 : begin d <= 13'b0001111111000; end
      8'h43 : begin d <= 13'b0001111111100; end
      8'h44 : begin d <= 13'b0011000000011; end
      8'h45 : begin d <= 13'b0011000000111; end
25     8'h46 : begin d <= 13'b0011000001100; end
      8'h47 : begin d <= 13'b0011000001111; end
      8'h48 : begin d <= 13'b0011000011000; end
      8'h49 : begin d <= 13'b0011000011100; end
      8'h4A : begin d <= 13'b0011000011111; end
30     8'h4B : begin d <= 13'b0011000110000; end
      8'h4C : begin d <= 13'b0011000110011; end
      8'h4D : begin d <= 13'b0011000111000; end
      8'h4E : begin d <= 13'b0011000111100; end
      8'h4F : begin d <= 13'b0011000111111; end
35     8'h50 : begin d <= 13'b0011001100000; end
      8'h51 : begin d <= 13'b0011001100011; end
      8'h52 : begin d <= 13'b0011001100111; end
      8'h53 : begin d <= 13'b0011001110000; end
      8'h54 : begin d <= 13'b0011001110011; end
40     8'h55 : begin d <= 13'b0011001111000; end
      8'h56 : begin d <= 13'b0011001111100; end
      8'h57 : begin d <= 13'b0011100000011; end
      8'h58 : begin d <= 13'b0011100000111; end
      8'h59 : begin d <= 13'b0011100001100; end
45     8'h5A : begin d <= 13'b0011100001111; end
      8'h5B : begin d <= 13'b0011100011000; end
      8'h5C : begin d <= 13'b0011100011100; end
      8'h5D : begin d <= 13'b0011100011111; end
      8'h5E : begin d <= 13'b0011100110000; end
50     8'h5F : begin d <= 13'b0011100110011; end
      8'h60 : begin d <= 13'b0011100111000; end

```

```

8'h61 : begin d <= 13'b001111001111100; end
8'h62 : begin d <= 13'b001111001111111; end
8'h63 : begin d <= 13'b001111100000011; end
8'h64 : begin d <= 13'b001111100000111; end
5 8'h65 : begin d <= 13'b001111100011100; end
8'h66 : begin d <= 13'b001111100011111; end
8'h67 : begin d <= 13'b00111110011000; end
8'h68 : begin d <= 13'b00111110011100; end
10 8'h69 : begin d <= 13'b001111100111111; end
8'h6A : begin d <= 13'b00111111000000; end
8'h6B : begin d <= 13'b00111111000011; end
8'h6C : begin d <= 13'b00111111000111; end
8'h6D : begin d <= 13'b00111111001100; end
15 8'h6E : begin d <= 13'b001111110011111; end
8'h6F : begin d <= 13'b00111111100000; end
8'h70 : begin d <= 13'b00111111100011; end
8'h71 : begin d <= 13'b00111111100111; end
8'h72 : begin d <= 13'b00111111110000; end
20 8'h73 : begin d <= 13'b00111111110011; end
8'h74 : begin d <= 13'b00111111111000; end
8'h75 : begin d <= 13'b00111111111100; end
8'h76 : begin d <= 13'b11000000000011; end
25 8'h77 : begin d <= 13'b11000000000111; end
8'h78 : begin d <= 13'b11000000001100; end
8'h79 : begin d <= 13'b11000000001111; end
8'h7A : begin d <= 13'b11000000011000; end
8'h7B : begin d <= 13'b11000000011100; end
8'h7C : begin d <= 13'b11000000011111; end
30 8'h7D : begin d <= 13'b1100000110000; end
8'h7E : begin d <= 13'b1100000110011; end
8'h7F : begin d <= 13'b1100000111000; end
8'h80 : begin d <= 13'b1100000111100; end
8'h81 : begin d <= 13'b1100000111111; end
35 8'h82 : begin d <= 13'b1100001100000; end
8'h83 : begin d <= 13'b1100001100011; end
8'h84 : begin d <= 13'b1100001100111; end
8'h85 : begin d <= 13'b1100001110000; end
8'h86 : begin d <= 13'b1100001110011; end
40 8'h87 : begin d <= 13'b1100001111000; end
8'h88 : begin d <= 13'b1100001111100; end
8'h89 : begin d <= 13'b1100011000000; end
8'h8A : begin d <= 13'b1100011000011; end
8'h8B : begin d <= 13'b1100011000111; end
45 8'h8C : begin d <= 13'b1100011001100; end
8'h8D : begin d <= 13'b1100011001111; end
8'h8E : begin d <= 13'b1100011100000; end
8'h8F : begin d <= 13'b1100011100011; end
50 8'h90 : begin d <= 13'b1100011100111; end
8'h91 : begin d <= 13'b1100011110000; end
8'h92 : begin d <= 13'b1100011110011; end
8'h93 : begin d <= 13'b1100011111000; end

```

```

8'h94 : begin d <= 13'b11000111111100; end
8'h95 : begin d <= 13'b11001100000011; end
8'h96 : begin d <= 13'b11001100000111; end
8'h97 : begin d <= 13'b11001100011100; end
5 8'h98 : begin d <= 13'b11001100011111; end
8'h99 : begin d <= 13'b1100110011000; end
8'h9A : begin d <= 13'b1100110011100; end
8'h9B : begin d <= 13'b1100110011111; end
10 8'h9C : begin d <= 13'b1100111000000; end
8'h9D : begin d <= 13'b1100111000011; end
8'h9E : begin d <= 13'b1100111000111; end
8'h9F : begin d <= 13'b1100111001100; end
8'hA0 : begin d <= 13'b1100111001111; end
15 8'hA1 : begin d <= 13'b1100111100000; end
8'hA2 : begin d <= 13'b1100111100011; end
8'hA3 : begin d <= 13'b1100111100111; end
8'hA4 : begin d <= 13'b1100111110000; end
8'hA5 : begin d <= 13'b1100111110011; end
20 8'hA6 : begin d <= 13'b1100111111000; end
8'hA7 : begin d <= 13'b1100111111100; end
8'hA8 : begin d <= 13'b1110000000011; end
8'hA9 : begin d <= 13'b1110000000111; end
25 8'hAA : begin d <= 13'b1110000001100; end
8'hAB : begin d <= 13'b1110000001111; end
8'hAC : begin d <= 13'b1110000011000; end
8'hAD : begin d <= 13'b1110000011100; end
8'hAE : begin d <= 13'b1110000011111; end
8'hAF : begin d <= 13'b1110000110000; end
30 8'hB0 : begin d <= 13'b1110000110011; end
8'hB1 : begin d <= 13'b1110000111000; end
8'hB2 : begin d <= 13'b1110000111100; end
8'hB3 : begin d <= 13'b1110000111111; end
8'hB4 : begin d <= 13'b1110001100000; end
35 8'hB5 : begin d <= 13'b1110001100011; end
8'hB6 : begin d <= 13'b1110001100111; end
8'hB7 : begin d <= 13'b1110001110000; end
8'hB8 : begin d <= 13'b1110001110011; end
8'hB9 : begin d <= 13'b1110001111000; end
40 8'hBA : begin d <= 13'b1110001111100; end
8'hBB : begin d <= 13'b1110011000000; end
8'hBC : begin d <= 13'b1110011000011; end
8'hBD : begin d <= 13'b1110011000111; end
8'hBE : begin d <= 13'b1110011001100; end
45 8'hBF : begin d <= 13'b1110011001111; end
8'hC0 : begin d <= 13'b1110011100000; end
8'hC1 : begin d <= 13'b1110011100011; end
8'hC2 : begin d <= 13'b1110011100111; end
8'hC3 : begin d <= 13'b1110011110000; end
50 8'hC4 : begin d <= 13'b1110011110011; end
8'hC5 : begin d <= 13'b1110011111000; end
8'hC6 : begin d <= 13'b1110011111100; end

```

```

8'hC7 : begin d <= 13'b1111000000011; end
8'hC8 : begin d <= 13'b1111000000111; end
8'hC9 : begin d <= 13'b1111000001100; end
8'hCA : begin d <= 13'b1111000001111; end
5 8'hCB : begin d <= 13'b1111000011000; end
8'hCC : begin d <= 13'b1111000011100; end
8'hCD : begin d <= 13'b1111000011111; end
8'hCE : begin d <= 13'b1111000110000; end
10 8'hCF : begin d <= 13'b1111000110011; end
8'hD0 : begin d <= 13'b1111000111000; end
8'hD1 : begin d <= 13'b1111000111100; end
8'hD2 : begin d <= 13'b1111000111111; end
8'hD3 : begin d <= 13'b1111001100000; end
15 8'hD4 : begin d <= 13'b1111001100011; end
8'hD5 : begin d <= 13'b1111001100111; end
8'hD6 : begin d <= 13'b1111001110000; end
8'hD7 : begin d <= 13'b1111001110011; end
8'hD8 : begin d <= 13'b1111001111000; end
20 8'hD9 : begin d <= 13'b1111001111100; end
8'hDA : begin d <= 13'b0000000110000; end
8'hDB : begin d <= 13'b1111100000011; end
8'hDC : begin d <= 13'b0000000110011; end
8'hDD : begin d <= 13'b1111100000111; end
25 8'hDE : begin d <= 13'b0000000111000; end
8'hDF : begin d <= 13'b1111100001100; end
8'hE0 : begin d <= 13'b0000000111100; end
8'hE1 : begin d <= 13'b1111100001111; end
8'hE2 : begin d <= 13'b0000000111111; end
30 8'hE3 : begin d <= 13'b1111100011000; end
8'hE4 : begin d <= 13'b0000001111111; end
8'hE5 : begin d <= 13'b1111100011100; end
8'hE6 : begin d <= 13'b0000110000000; end
8'hE7 : begin d <= 13'b1111100011111; end
35 8'hE8 : begin d <= 13'b0001110000000; end
8'hE9 : begin d <= 13'b1111100110000; end
8'hEA : begin d <= 13'b0011001111111; end
8'hEB : begin d <= 13'b1111100110011; end
8'hEC : begin d <= 13'b0011110000000; end
40 8'hED : begin d <= 13'b1111100111000; end
8'hEE : begin d <= 13'b1100001111111; end
8'hEF : begin d <= 13'b1111100111100; end
8'hF0 : begin d <= 13'b1100110000000; end
8'hF1 : begin d <= 13'b1111100111111; end
45 8'hF2 : begin d <= 13'b1110001111111; end
8'hF3 : begin d <= 13'b1111001111111; end
8'hF4 : begin d <= 13'b1111110000000; end
8'hF5 : begin d <= 13'b1111110000011; end
8'hF6 : begin d <= 13'b0000000011000; end
50 8'hF7 : begin d <= 13'b1111110000111; end
8'hF8 : begin d <= 13'b0000000011100; end
8'hF9 : begin d <= 13'b1111110001100; end

```

```

5          8'hFA : begin d <= 13'b0000000011111; end
          8'hFB : begin d <= 13'b1111110001111; end
          8'hFC : begin d <= 13'b0000011111111; end
          8'hFD : begin d <= 13'b1111110011000; end
          8'hFE : begin d <= 13'b0001100000000; end
          8'hFF : begin d <= 13'b1111110011100; end
          default : begin end
        endcase
        end
10      end

        assign out[0] = d[12]; // correct order: MSB is "m", LSB is "a"
        (going output first)
        assign out[1] = d[11];
15      assign out[2] = d[10];
        assign out[3] = d[9];
        assign out[4] = d[8];
        assign out[5] = d[7];
20      assign out[6] = d[6];
        assign out[7] = d[5];
        assign out[8] = d[4];
        assign out[9] = d[3];
        assign out[10] = d[2];
        assign out[11] = d[1];
25      assign out[12] = d[0];

        endmodule

```

Appendix B

Example C++ Program for determining a valid code table

```

/*
5   This program finds codes for determined code length, minimum and maximum number
of repetitive bits.
   usage:      cf      Number_of_bits_in_code      Minimum_pulse_width_in_bits
Maximum_pulse_width_in_bits Output_file_name
*/
10
   #include      <stdio.h>
   #include      <string.h>
   #include      <math.h>
   #include      <stdlib.h>
15
   // maximum number of chars in text string
   #define MAXL 256

   // maximum code length
20  #define MAXLENGTH 16

   // maximum codes on the output
   #define MAXCODES 2048

25  // enable extra sorting
   #define EXTRA_SORT_EN 0

   int          length, min, max;
   int          min_bits, max_bits, mid_en;
30  int          nc;
   int          c[MAXCODES];

   int          dsm[MAXCODES];
   int          dsp[MAXCODES];
35  int          cntm, cntp;

   int          rm[MAXCODES];
   int          rp[MAXCODES];
   int          cntrm, cntrp;
40
   int          wt[MAXCODES];
   int          depth;
   int          presc, iter;

45  char  weight[2<<(MAXLENGTH-1)];

```

```

int          cmp[MAXCODES][MAXCODES];

char  *ofile_name;

5   int          start, end, top_en, dc_bal_en;
    int          sm[MAXCODES];
    int          sp[MAXCODES];
    int          smc, spc;
    int          minm, minp;

10  FILE  *ofile;

    void sec(n)

15  int    n;

    {
        int    i, j, k, l;
        do {
20            k=0;
            minm=cntp;
            minp=cntm;
            for(i=0; i<cntm; i++) {
                l=0;
25                for(j=0; j<cntp; j++) l+=cmp[dsm[i]][dsp[j]] & cmp[dsp[j]][dsm[i]];
                if(l<n) {
                    k++;
                    sm[smc++]=dsm[i];
                    cntm--;
30                    for(j=i; j<cntm; j++) dsm[j]=dsm[j+1];
                }
                else minm=min(minm,l);
            }
            for(i=0; i<cntp; i++) {
35                l=0;
                for(j=0; j<cntm; j++) l+=cmp[dsm[j]][dsp[i]] & cmp[dsp[i]][dsm[j]];
                if(l<n) {
                    k++;
                    sp[spc++]=dsp[i];
40                    cntp--;
                    for(j=i; j<cntp; j++) dsp[j]=dsp[j+1];
                }
                else minp=min(minp,l);
            }
45            if(dc_bal_en!=0) {

```



```

    for(i=0; i<cntm; i++) {
        if(weight[dsm[i]]==mid_en) {
            l=0;
            for(j=0; j<cntm; j++) l+=cmp[dsm[i]][dsm[j]] &
5      cmp[dsm[j]][dsm[i]];

            if(l<n) {
                k++;
                sm[smc++]=dsm[i];
                cntm--;
10          for(j=i; j<cntm; j++) dsm[j]=dsm[j+1];
            }
            else minm=min(minm,l);
        }
    }
15  for(i=0; i<cntp; i++) {
        if(weight[dsp[i]]==mid_en) {
            l=0;
            for(j=0; j<cntp; j++) l+=cmp[dsp[j]][dsp[i]] &
20      cmp[dsp[i]][dsp[j]];

            if(l<n) {
                k++;
                sp[spc++]=dsp[i];
                cntp--;
25          for(j=i; j<cntp; j++) dsp[j]=dsp[j+1];
            }
            else minp=min(minp,l);
        }
    }
30  } while(k!=0);
}

void sort(void)
{
35      int      i, j, k, l, m, repm, repp, lm, lp, wi, wm, wp, wb;
      double wc;
      int      conm[MAXCODES];
      int      conp[MAXCODES];

40      for(i=0; i<cntp; i++) {
          conp[i]=0;
          for(j=0; j<cntm; j++) {
              conp[i]+=((cmp[dsm[j]][dsp[i]]==0)||((cmp[dsp[i]][dsm[j]]==0))?)1:0;
45          }
      }

```

```

    }

    for(i=0; i<cntm; i++) {
        conm[i]=0;
5        for(j=0; j<cntp; j++) {
            conm[i]+=((cmp[dsm[i]][dsp[j]]==0)||((cmp[dsp[j]][dsm[i]]==0)?1:0);
        }
    }

10    for(i=0; i<cntp; i++) {
        for(j=0; j<i; j++) {
            if(conp[j]>conp[j+1]) {
                k=conp[j];
                conp[j]=conp[j+1];
15                conp[j+1]=k;
                k=dsp[j];
                dsp[j]=dsp[j+1];
                dsp[j+1]=k;
            }
        }
20    }

    for(i=0; i<cntm; i++) {
        for(j=0; j<i; j++) {
25            if(conm[j]>conm[j+1]) {
                k=conm[j];
                conm[j]=conm[j+1];
                conm[j+1]=k;
                k=dsm[j];
                dsm[j]=dsm[j+1];
30                dsm[j+1]=k;
            }
        }
    }
35

    if(EXTRA_SORT_EN!=0) {
        wc=0.;
        for(i=0; i<cntm; i++) {
            k=(cntm-i)*(cntm-i);
40            for(j=0; j<cntp; j++) wc+=((cntp-j)*(cntp-j)+k)*(1-
                (cmp[dsm[i]][dsp[j]]&cmp[dsp[j]][dsm[i]]));
            if(wt[dsm[i]]==mid_en) for(j=0; j<cntm; j++) wc+=(cntm-j)*(cntm-
                j)*(1-(cmp[dsm[i]][dsm[j]]&cmp[dsm[j]][dsm[i]]));
45        }
    }

```

```

    for(i=0; i<cntm; i++) {
        printf("Sorting iteration %d%%, current weight is %d
5         \r", (i*100)/cntm, wc);
        exit(0);
        for(j=0; j<cntp; j++) {
            for(k=0; k<cntm; k++) {
                for(l=0; l<cntp; l++) {
                    // try to swap row,col i,j, with k,l. if total weight is less then leave it.
                    // count difference of swapping m
10                    wm=0;
                    for(m=0; m<cntp; m++) wm+=((cntp-
m)*(cntp-m)+k)*(1-(cmp[dsm[i]][dsp[j]]&cmp[dsp[j]][dsm[i]]));

15                    }
                }
            }
        }
        printf("\n");
20    }
    lm=0;
    lp=0;
    for(i=0; i<max(cntm, cntp); i++) {
        if(i<cntm) {
25            repp=0;
            for(j=0; j<min(cntp, i+1); j++) {
                if((cmp[dsm[i]][dsp[j]]==0)||((cmp[dsp[j]][dsm[i]]==0)) {
                    for(k=lp+1; k<cntp; k++) {
                        repp=0;
30                        for(l=0; l<=i; l++) {
                            if((cmp[dsm[l]][dsp[k]]==0)||((cmp[dsp[k]][dsm[l]]==0)) {
                                repp=1;
                                break;
35                            }
                        }
                    }
                    if(repp==0) {
                        l=dsp[k];
                        for(; k>j; k--) dsp[k]=dsp[k-1];
                        dsp[j]=l;
                        break;
40                    }
                }
            }
        }
        if(repp!=0) break;
45    }

```

```

    }
    if(repp==0) lp++;
}

5      if(i<cntp) {
        repm=0;
        for(j=0; j<min(cntm,i+1); j++) {
            if((cmp[dsm[j]][dsp[i]]==0)||((cmp[dsp[i]][dsm[j]]==0)) {
10                for(k=lm+1; k<cntm; k++) {
                    repm=0;
                    for(l=0; l<=i; l++) {

15                        if((cmp[dsm[k]][dsp[l]]==0)||((cmp[dsp[l]][dsm[k]]==0)) {
                            repm=1;
                            break;
                        }
                    }
                if(repm==0) {
20                    l=dsm[k];
                    for(; k>j; k--) dsm[k]=dsm[k-1];
                    dsm[j]=l;
                    break;
                }
            }
        }
        if(repm!=0) break;
    }
    if(repm==0) lm++;
}
30      if((repp!=0)&&(repm!=0)) break;
}

    printf("lm=%d lp=%d\n",lm,lp);
}

35      // dump results

void dump(void)
{
40      int    i, j;

        if ((ofile=fopen(ofile_name, "w"))==NULL){
            printf("Can't open \"%s\" for write\n", ofile_name);
            exit(1);
45      }
    }

```

```

5      fprintf(ofile, "-\n");
      for(i=1; i<cntm; i++) {
          for(j=length-1; j>=0; j--) {
              fprintf(ofile, "%d", (c[dsrm[i]]>j)&1);
          }
          fprintf(ofile, "\n");
      }

10     fprintf(ofile, "+\n");
      for(i=1; i<cntp; i++) {
          for(j=length-1; j>=0; j--) {
              fprintf(ofile, "%d", (c[dsp[i]]>j)&1);
          }
          fprintf(ofile, "\n");
      }

15     fprintf(ofile, "removed -\n");
      for(i=0; i<cntrm; i++) {
          for(j=length-1; j>=0; j--) {
              fprintf(ofile, "%d", (c[rm[i]]>j)&1);
          }
          fprintf(ofile, "\n");
      }

20     fprintf(ofile, "removed +\n");
      for(i=0; i<cntrp; i++) {
          for(j=length-1; j>=0; j--) {
              fprintf(ofile, "%d", (c[rp[i]]>j)&1);
          }
          fprintf(ofile, "\n");
      }

25     fclose(ofile);
35 }

```

// remove one code and try to test for conflicts, if failed try to remove another and test again. Recursive!!!

```

40 int r(f, s, type)
    {
        int      f, s, type;
        int      i, j;
45

```

```

//      printf("r(f=%d s=%d, type=%d) at level %d\n",f,s,type,cntrm+cntrp);

      if(type==0) {
          if(wt[dsm[f]]==mid_en) {
5              cntm--;

              rm[cntrm++]=dsm[f];
              for(i=f; i<cntm; i++) dsm[i]=dsm[i+1];
              j=test();
10              if(j>0) return(j);
              for(i=cntm; i>f; i--) dsm[i]=dsm[i-1];
              dsm[f]=rm[--cntrm];

              rm[cntrm++]=dsm[s];
              for(i=s; i<cntm; i++) dsm[i]=dsm[i+1];
              j=test();
15              if(j>0) return(j);
              for(i=cntm; i>s; i--) dsm[i]=dsm[i-1];
              dsm[s]=rm[--cntrm];

              cntm++;
          }
          else if(cntm>cntp) {
25              cntm--;

              rm[cntrm++]=dsm[f];
              for(i=f; i<cntm; i++) dsm[i]=dsm[i+1];
              j=test();
              if(j>0) return(j);
30              for(i=cntm; i>f; i--) dsm[i]=dsm[i-1];
              dsm[f]=rm[--cntrm];

              cntm++;

              if(cntp>depth) {
35                  cntp--;

                  rp[cntrp++]=dsp[s];
                  for(i=s; i<cntp; i++) dsp[i]=dsp[i+1];
                  j=test();
40                  if(j>0) return(j);
                  for(i=cntp; i>s; i--) dsp[i]=dsp[i-1];
                  dsp[s]=rp[--cntrp];

                  cntp++;
45

```

```

    }
}
else {
5      cntp--;

      rp[cntrp++] = dsp[s];
      for(i=s; i<cntp; i++) dsp[i] = dsp[i+1];
      j=test();
      if(j>0) return(j);
10     for(i=cntp; i>s; i--) dsp[i] = dsp[i-1];
      dsp[s] = rp[--cntrp];

      cntp++;

15     if(cntm>depth) {
          cntm--;

          rm[cntrm++] = dsm[f];
          for(i=f; i<cntm; i++) dsm[i] = dsm[i+1];
20         j=test();
          if(j>0) return(j);
          for(i=cntm; i>f; i--) dsm[i] = dsm[i-1];
          dsm[f] = rm[--cntrm];

          cntm++;
25     }
    }
}
else {
30     if(wt[dsp[f]] == mid_en) {
        // printf("here ----- \n");
        cntp--;

        rp[cntrp++] = dsp[f];
        for(i=f; i<cntp; i++) dsp[i] = dsp[i+1];
        j=test();
        if(j>0) return(j);
        for(i=cntp; i>f; i--) dsp[i] = dsp[i-1];
        dsp[f] = rp[--cntrp];
35
        rp[cntrp++] = dsp[s];
        for(i=s; i<cntp; i++) dsp[i] = dsp[i+1];
        j=test();
        if(j>0) return(j);
        for(i=cntp; i>s; i--) dsp[i] = dsp[i-1];
40
        rp[cntrp++] = dsp[s];
        for(i=s; i<cntp; i++) dsp[i] = dsp[i+1];
        j=test();
        if(j>0) return(j);
        for(i=cntp; i>s; i--) dsp[i] = dsp[i-1];
45
    }
}

```

```

        dsp[s]=rp[--cntrp];

        cntp++;
    }
5   else if(cntm>cntp) {
        cntm--;

        rm[cntrm++]=dsm[s];
        for(i=s; i<cntm; i++) dsm[i]=dsm[i+1];
10   j=test();
        if(j>0) return(j);
        for(i=cntm; i>s; i--) dsm[i]=dsm[i-1];
        dsm[s]=rm[--cntrm];

15   cntm++;

        if(cntp>depth) {
            cntp--;

20   rp[cntrp++]=dsp[f];
            for(i=f; i<cntp; i++) dsp[i]=dsp[i+1];
            j=test();
            if(j>0) return(j);
            for(i=cntp; i>f; i--) dsp[i]=dsp[i-1];
25   dsp[f]=rp[--cntrp];

            cntp++;
        }
    }
30   else {
        cntp--;

        rp[cntrp++]=dsp[f];
        for(i=f; i<cntp; i++) dsp[i]=dsp[i+1];
35   j=test();
        if(j>0) return(j);
        for(i=cntp; i>f; i--) dsp[i]=dsp[i-1];
        dsp[f]=rp[--cntrp];

40   cntp++;

        if(cntm>depth) {
            cntm--;

45   rm[cntrm++]=dsm[s];

```



```

    for(i=s; i<cntm; i++) dsm[i]=dsm[i+1];
    j=test();
    if(j>0) return(j);
    for(i=cntm; i>s; i--) dsm[i]=dsm[i-1];
    dsm[s]=rm[--cntrm];

    cntm++;
}
}
}
return(-1);
}

// Check compatibility of current set and in case of conflicts tries to remove codes using
r() Recursive!!!

int test(void) {
    int i, j;
    presc=(presc+1)&0xfffff;
    if(presc==0) printf("iteration %d\r",iter++);
    // printf("depth=%d cntm=%d cntp=%d\n",depth,cntm,cntp);
    for(i=(cntm-1); i>=0; i--) {
        if(wt[dsm[i]]==mid_en) {
            for(j=(cntm-1); j>=0; j--) {
                if(cmp[dsm[i]][dsm[j]]==0) {
                    if(cntm>depth) return(r(i,j,0));
                    else return(-1);
                }
            }
        }
        else {
            for(j=(cntp-1); j>=0; j--) {
                if(cmp[dsm[i]][dsp[j]]==0) {
                    if(max(cntm,cntp)>depth) return(r(i,j,0));
                    else return(-1);
                }
            }
        }
    }

    // printf("half depth=%d cntm=%d cntp=%d\n",depth,cntm,cntp);

    for(i=(cntp-1); i>=0; i--) {
        if(wt[dsp[i]]==mid_en) {

```

```

    for(j=(cntp-1); j>=0; j--) {
        if(cmp[dsp[i]][dsp[j]]==0) {
            if(cntp>depth) return(r(i,j,1));
            else return(-1);
        }
    }
}
else {
    for(j=(cntm-1); j>=0; j--) {
        if(cmp[dsp[i]][dsm[j]]==0) {
            if(max(cntm,cntp)>depth) return(r(i,j,1));
            else return(-1);
        }
    }
}
printf("\nDone\n");
dump();
return(depth);
}

// if minimum pulse width in word code with length len not less than min
// and maximum pulse width is less or equal to max then returns 1 else 0

int inrange(code, len)
{
    int      code, len;

    int      i, j, k, l, m;

    i=code&1;    // current bit
    j=1;         // same bits count
    k=-1;        // minimum
    l=0;         // maximum
    for(m=1; m<len; m++){
        if(((code>>m)&1)==i) j++;
        else {
            if(k<0) k=len;
            else k=min(k,j);
            l=max(l,j);
            i=i^1;
            j=1;
        }
    }
    l=max(l,j);

```

```

        return((((k>=min)||((k<0))&&(l<=max)) ? 1 : 0);
    }

    int    main (argc, argv)
5
        int        argc;
        char    **argv;
    {
        int        i, j, k, l;
10
        if (argc != 9) {
            printf("Usage:      cf      LENGTH      MINIMUM_PULSE_WIDTH
MAXIMUM_PULSE_WIDTH      START      END      TOP_TO_BOT_EN      DC_BAL_EN
output_file_name\n");
15
            exit(1);
        }

        sscanf(argv[1], "%d", &length);
        sscanf(argv[2], "%d", &min);
        sscanf(argv[3], "%d", &max);
        sscanf(argv[4], "%d", &start);
        sscanf(argv[5], "%d", &end);
        sscanf(argv[6], "%d", &top_en);
        sscanf(argv[7], "%d", &dc_bal_en);
20
        if(((min<=0)||((max<min))||((2*length<max))||((length>MAXLENGTH))) {
            printf("Wrong      parameters      value.\nUsage:      cf      LENGTH
MINIMUM_PULSE_WIDTH      MAXIMUM_PULSE_WIDTH      START      END      TOP_TO_BOT_EN
DC_BAL_EN output_file_name\n");
25
            exit(1);
        }

        ofile_name=argv[8];

35
        // prepare for calculation
        min_bits=(dc_bal_en!=0)?(length-1)/2:0;    // minimum and maximum ones in
code for DC balance
        max_bits=(dc_bal_en!=0)?(length+2)/2:0;

40
        // -1 if 2 different weights used (odd code length) or if dc balance disabled, otherwise
weight of the middle
        mid_en=((((max_bits-min_bits)==2)&&((dc_bal_en!=0)))?(max_bits+min_bits)/2:-
1;

45
        // prepare weight decoding table

```

```

        for(i=0; i<(2<<(length-1)); i++){
            weight[i]=0;
            if(dc_bal_en!=0) for(j=0; j<length; j++) weight[i]+=(i>j)&1;
        }
5
    // make initial filtering by finding codes which meets minimum and maximum pule
    requirements
    // and DC balance requirements
    // collect result in the stack c[]. nc - original number of codes.
10
    nc=0;
    for(i=0; i<(2<<(length-1)); i++) {
        if((weight[i]>=min_bits)&&(weight[i]<=max_bits)) {
            if(inrange(i,length)!=0) {
                if(nc<(MAXCODES-1)) c[nc++]=i;
15
                else printf("Too many input codes, ignore %x\n",i);
            }
        }
    }

20
    // create compatibility table. first argument - first simbol in the channel
    for(i=0; i<nc; i++) {
        for(j=0; j<nc; j++) {
            cmp[i][j]=inrange((c[i]<<length)|c[j],2*length);
25
        }
    }

    // split all codes onto two groups: suitable for disparity -,+ and calculate weight of codes
30
    cntm=0;
    cntp=0;
    for(i=0; i<nc; i++) {
        wt[i]=weight[c[i]];
        if(((wt[i]<max_bits)&&((cmp[i][i]==1)||wt[i]!=mid_en))||(dc_bal_en==0))
35
        dsm[cntm++]=i;
        if(((wt[i]>min_bits)&&((cmp[i][i]==1)||wt[i]!=mid_en))||(dc_bal_en==0))
        dsp[cntp++]=i;
    }

    printf("found %d:%d codes\n",cntm,cntp);
40

    // analize
    smc=0;
    spc=0;
    for(i=start; i<=end; i++) {
45
        sec(i);
    }

```

```

        if(min(minp,minm)>=i) printf("for %d codes matrix size is
        %dx%d\n",i,cntm,cntp);
        else end=i-1;
    }
5
    for( smc>0; ) dsm[cntm++]=sm[--smc];
    for( spc>0; ) dsp[cntp++]=sp[--spc];

    sec(start);
10
    // start iterations
    cntrm=0;
    cntrp=0;
    iter=0;
15
    presc=0;

    if(top_en!=0) {
        depth=end;
        spc=0;
        smc=0;
20
        do {
            for( smc>0; ) dsm[cntm++]=sm[--smc];
            for( spc>0; ) dsp[cntp++]=sp[--spc];
            for( cntrm>0; ) dsm[cntm++]=rm[--cntrm];
            for( cntrp>0; ) dsp[cntp++]=rp[--cntrp];
25
            printf("\ntry to find %3d codes\n",depth);
            sec(depth);
            sort();
            if ((ofile=fopen("bitmap.txt", "w"))==NULL){
30
                printf("Can't open bitmap.txt for write\n");
                exit(1);
            }
            for(i=0; i<nc; i++) {
                for(j=0; j<nc; j++) {
35
                    fprintf(ofile,"%d",1-
(cmp[dsm[j]][dsp[i]]&cmp[dsp[i]][dsm[j]]));
                }
                fprintf(ofile,"\n");
            }
40
            fclose(ofile);

        } while((test()<0)&&(depth-->start));
    }
    else {
45
        depth=start-1;
    }

```

```

do {
    for(; cntm>0; ) dsm[cntm++]=rm[--cntm];
    for(; cntp>0; ) dsp[cntp++]=rp[--cntp];
    printf("\ntry to find %3d codes\n",++depth);
5    sec(depth);
    sort();
    if ((ofile=fopen("bitmap.txt", "w"))==NULL){
        printf("Can't open bitmap.txt for write\n");
        exit(1);
10    }
    for(i=0; i<nc; i++) {
        for(j=0; j<nc; j++) {
            fprintf(ofile,"%d",1-
15    (cmp[dsm[j]][dsp[i]]&cmp[dsp[i]][dsm[j]]));
        }
        fprintf(ofile,"\n");
    }
    fclose(ofile);
    } while((cntp>=depth)&&(cntm>=depth)&&(test(>0)));
20    if(min(cntp,cntm)<depth) printf("Can not find code with %d
symbols\n",depth);
    }
25    exit(0);
}

```

Appendix C: Code table for 8b/16b encoding with the same criteria of DC balance, minimum pulse width and maximum transition interval.

Table 1			
Negative disparity table			
5	1. 0000001111000111	50	39. 0000111001111000
	2. 0000001111001111		40. 0000111001111100
10	3. 000000111100011		41. 0000111100000111
	4. 000000111100111		42. 0000111100001111
	5. 000000111110011		43. 0000111100011100
	6. 000000111111000	55	44. 0000111100110011
	7. 000000111111100		45. 0000111100111000
15	8. 0000011001100111		46. 0000111100111100
	9. 0000011001110011		47. 0000111110000011
	10. 0000011001111100		48. 0000111110000111
	11. 000001100001111	60	49. 0000111110001100
	12. 000001100110011		50. 0000111110011000
20	13. 000001100111100		51. 0000111110011100
	14. 000001110000111		52. 0000111111000011
	15. 000001110001111		53. 0000111111001100
	16. 000001110011100	65	54. 0001100001100111
	17. 000001111000011		55. 0001100001110011
25	18. 000001111000111		56. 0001100001111100
	19. 000001111001100		57. 0001100011000111
	20. 000001111100011	70	58. 0001100011001111
	21. 000001111110000		59. 0001100011100011
30	22. 000001111111000		60. 0001100011100111
	23. 000011000110011		61. 0001100011110011
	24. 0000110001110011		62. 0001100011111000
	25. 0000110001111100		63. 0001100011111100
	26. 0000110011000111	75	64. 0001100110000111
	27. 000011001100111		65. 0001100110001111
35	28. 0000110011100011		66. 0001100110011100
	29. 0000110011100111		67. 0001100111000011
	30. 0000110011110011		68. 0001100111000111
	31. 0000110011111000	80	69. 0001100111001100
	32. 0000110011111100		70. 0001100111100011
40	33. 0000111000001111		71. 0001100111110000
	34. 0000111000110011		72. 0001100111111000
	35. 0000111000111100		73. 0001110000001111
	36. 0000111001100011	85	74. 0001110000110011
	37. 0000111001100111		75. 0001110000111100
45	38. 0000111001110011		76. 0001110001100011
			77. 0001110001100111
			78. 0001110001110011
			79. 0001110001111000
			80. 0001110001111100

	81.	0001110011000011		126.	0011001100001111
	82.	0001110011000111		127.	0011001100011100
	83.	0001110011001100		128.	0011001100110011
5	84.	0001110011100011		129.	0011001100111000
	85.	0001110011110000	50	130.	0011001100111100
	86.	0001110011111000		131.	0011001110000011
	87.	0001111000000111		132.	0011001110000111
	88.	0001111000001111		133.	0011001110001100
10	89.	0001111000011100		134.	0011001110011000
	90.	0001111000110011	55	135.	0011001110011100
	91.	0001111000111000		136.	0011001111000011
	92.	0001111000111100		137.	0011001111001100
15	93.	0001111001100011		138.	0011001111100000
	94.	0001111001110000		139.	0011100000001111
	95.	0001111001111000	60	140.	0011100000110011
	96.	0001111100000011		141.	0011100000111100
	97.	0001111100000111		142.	0011100001100011
	98.	0001111100001100		143.	0011100001100111
20	99.	0001111100011000		144.	0011100001110011
	100.	0001111100011100	65	145.	0011100001111000
	101.	0001111100110000		146.	0011100001111100
	102.	0001111100111000		147.	0011100011000011
	103.	0001111110000011		148.	0011100011000111
25	104.	0001111110001100		149.	0011100011001100
	105.	0001111110011000	70	150.	0011100011100011
	106.	0011000001100111		151.	0011100011110000
	107.	0011000001110011		152.	0011100011111000
	108.	0011000001111100		153.	0011100110000011
30	109.	0011000011000111		154.	0011100110000111
	110.	0011000011001111	75	155.	0011100110001100
	111.	0011000011100011		156.	0011100110011000
	112.	0011000011100111		157.	0011100110011100
	113.	0011000011110011		158.	0011100111000011
35	114.	0011000011111000		159.	0011100111001100
	115.	0011000011111100	80	160.	0011100111100000
	116.	0011000110000111		161.	0011110000000111
	117.	0011000110001111		162.	0011110000001111
	118.	0011000110011100		163.	0011110000011100
40	119.	0011000111000011		164.	0011110000110011
	120.	0011000111000111	85	165.	0011110000111000
	121.	0011000111001100		166.	0011110000111100
	122.	0011000111100011		167.	0011110001100011
	123.	0011000111110000		168.	0011110001110000
	124.	0011000111111000		169.	0011110001111000
45	125.	0011001100000111	90	170.	0011110011000011

	171.	0011110011001100		216.	1100001111100000
	172.	0011110011100000		217.	1100011000000111
	173.	0011111000000011		218.	1100011000001111
5	174.	0011111000000111		219.	1100011000011100
	175.	0011111000001100	50	220.	1100011000110011
	176.	0011111000011000		221.	1100011000111000
	177.	0011111000011100		222.	1100011000111100
	178.	0011111000110000		223.	1100011001100011
10	179.	0011111000111000		224.	1100011001110000
	180.	0011111001100000	55	225.	1100011001111000
	181.	0011111100000011		226.	1100011100000011
	182.	0011111100001100		227.	1100011100000111
	183.	0011111100011000		228.	1100011100001100
15	184.	1100000001100111		229.	1100011100011000
	185.	1100000001110011	60	230.	1100011100011100
	186.	1100000001111100		231.	1100011100110000
	187.	1100000001100011		232.	1100011100111000
	188.	1100000001100111		233.	1100011110000011
20	189.	1100000001110001		234.	1100011110001100
	190.	1100000001110011	65	235.	1100011110011000
	191.	1100000001111001		236.	1100110000000111
	192.	1100000001111000		237.	1100110000001111
	193.	1100000001111100		238.	1100110000011100
25	194.	1100000110000111		239.	1100110000110011
	195.	1100000110001111	70	240.	1100110000111000
	196.	1100000110011100		241.	1100110000111100
	197.	1100000111000011		242.	1100110001100011
	198.	1100000111000111		243.	1100110001110000
30	199.	1100000111001100		244.	1100110001111000
	200.	1100000111100011	75	245.	1100110011000011
	201.	1100000111110000		246.	1100110011001100
	202.	1100000111110000		247.	1100110011100000
	203.	1100001100000111		248.	1100111000000011
35	204.	1100001100001111		249.	1100111000000111
	205.	1100001100011100	80	250.	1100111000001100
	206.	1100001100110011		251.	1100111000011000
	207.	1100001100111000		252.	1100111000011100
	208.	1100001100111100		253.	1100111000110000
40	209.	1100001110000011		254.	1100111000111000
	210.	1100001110000111	85	255.	1100111001100000
	211.	1100001110001100		256.	1100111100000011
	212.	1100001110011000		257.	1100111100011000
	213.	1100001110011100		258.	1110000000001111
	214.	1100001111000011		259.	1110000000110011
45	215.	1100001111001100	90	260.	1110000000111100

5	261.	1110000001100011	50	306.	1111000000111100
	262.	1110000001100111		307.	1111000001100011
	263.	1110000001110011		308.	1111000001110000
	264.	1110000001111000		309.	1111000001111000
	265.	1110000001111100		310.	1111000011000011
10	266.	1110000011000011	55	311.	1111000011001100
	267.	1110000011000111		312.	1111000011100000
	268.	1110000011001100		313.	1111000110000011
	269.	1110000011100011		314.	1111000110001100
	270.	1110000011110000		315.	1111000110011000
15	271.	1110000011111000	60	316.	1111001100000011
	272.	1110000110000011		317.	1111001100001100
	273.	1110000110000111		318.	1111001100011000
	274.	1110000110001100		Positive disparity codes	
	275.	1110000110011000		1.	0000110011001111
20	276.	1110000110011100	65	2.	0000110011100111
	277.	1110000111000011		3.	0000110011110011
	278.	1110000111001100		4.	0000110011111100
	279.	1110000111100000		5.	0000110011001111
	280.	1110001100000011		6.	0000110011100111
25	281.	1110001100000111	70	7.	0000111001111100
	282.	1110001100001100		8.	0000111100001111
	283.	1110001100011000		9.	0000111100110011
	284.	1110001100011100		10.	0000111100111100
	285.	1110001100110000		11.	0000111110000111
30	286.	1110001100111000	75	12.	0000111110001111
	287.	1110001110000011		13.	0000111110011100
	288.	1110001110001100		14.	0000111111000011
	289.	1110001110011000		15.	0000111111000111
	290.	1110011000000011		16.	0000111111001100
35	291.	1110011000000111	80	17.	0000111111000111
	292.	1110011000001100		18.	0000111111100000
	293.	1110011000011000		19.	0000111111110000
	294.	1110011000011100		20.	0001100011001111
	295.	1110011000110000		21.	0001100011100111
40	296.	1110011000111000	85	22.	0001100011110011
	297.	1110011001100000		23.	0001100011111100
	298.	1110011100000011		24.	0001100110001111
	299.	1110011100001100		25.	0001100111000111
	300.	1110011100011000		26.	0001100111001111
45	301.	1111000000000111	90	27.	0001100111100011
	302.	1111000000001111		28.	0001100111100111
	303.	1111000000011100		29.	0001100111110011
	304.	1111000000110011			
	305.	1111000000111000			

	30. 0001100111111000		75. 0011000111111100
	31. 0001100111111100		76. 0011001100001111
	32. 0001110001100111		77. 0011001100110011
5	33. 0001110001110011	50	78. 0011001100111100
	34. 0001110001111100		79. 0011001110000111
	35. 0001110011000111		80. 0011001110001111
	36. 0001110011001111		81. 0011001110011100
	37. 0001110011100011		82. 0011001111000011
10	38. 0001110011100111	55	83. 0011001111000111
	39. 0001110011110011		84. 0011001111001100
	40. 0001110011111000		85. 0011001111100011
	41. 0001110011111100		86. 0011001111110000
15	42. 0001111000001111	60	87. 0011001111111000
	43. 0001111000110011		88. 0011100001100111
	44. 0001111000111100		89. 0011100001110011
	45. 0001111001100011		90. 0011100001111100
	46. 0001111001100111		91. 0011100011000111
	47. 0001111001110011		92. 0011100011001111
20	48. 0001111001111000	65	93. 0011100011100011
	49. 0001111001111100		94. 0011100011100111
	50. 0001111100000111		95. 0011100011110011
	51. 0001111100001111		96. 0011100011111000
	52. 0001111100011100		97. 0011100011111100
25	53. 0001111100110011	70	98. 0011100110000111
	54. 0001111100111000		99. 0011100110001111
	55. 0001111100111100		100. 0011100110011100
	56. 0001111110000011		101. 0011100111000011
	57. 0001111110000111		102. 0011100111000111
30	58. 0001111110001100	75	103. 0011100111001100
	59. 0001111110011000		104. 0011100111100011
	60. 0001111110011100		105. 0011100111110000
	61. 0001111111000011		106. 0011100111111000
	62. 0001111111001100		107. 0011110000001111
	63. 0001111111100000		108. 0011110000011111
35	64. 0011000011001111	80	109. 0011110000110011
	65. 0011000011100111		110. 0011110000111100
	66. 0011000011110011		111. 0011110001100011
	67. 0011000011111100		112. 0011110001100111
40	68. 0011000110001111	85	113. 0011110001110011
	69. 0011000111000111		114. 0011110001111000
	70. 0011000111001111		115. 0011110001111100
	71. 0011000111100011		116. 0011110011000011
	72. 0011000111100111		117. 0011110011000111
	73. 0011000111110011		118. 0011110011001100
45	74. 0011000111111000	90	119. 0011110011100011

	120.	0011110011110000		165.	1100001111110000
	121.	0011110011111000		166.	1100001111111000
	122.	0011111000000111		167.	1100011000001111
	123.	0011111000001111		168.	1100011000011111
5	124.	0011111000011100	50	169.	1100011000110011
	125.	0011111000110011		170.	1100011000111100
	126.	0011111000111000		171.	1100011001100011
	127.	0011111000111100		172.	1100011001100111
	128.	0011111001100011		173.	1100011001110011
10	129.	0011111001110000	55	174.	1100011001111000
	130.	0011111001111000		175.	1100011001111100
	131.	0011111100000011		176.	1100011100000111
	132.	0011111100000111		177.	1100011100001111
	133.	0011111100001100		178.	1100011100011100
15	134.	0011111100011000	60	179.	1100011100110011
	135.	0011111100011100		180.	1100011100111000
	136.	0011111100110000		181.	1100011100111100
	137.	0011111100111000		182.	1100011110000011
	138.	0011111110000011		183.	1100011110000111
20	139.	0011111110001100	65	184.	1100011110001100
	140.	0011111110011000		185.	1100011110011000
	141.	1100000011001111		186.	1100011110011100
	142.	1100000011100111		187.	1100011111000011
	143.	1100000011110011		188.	1100011111001100
25	144.	1100000011111100	70	189.	1100011111100000
	145.	1100000110001111		190.	1100110000001111
	146.	1100000110011111		191.	1100110000011111
	147.	1100000111000111		192.	1100110000110011
	148.	1100000111001111		193.	1100110000111100
30	149.	1100000111100011	75	194.	1100110001100011
	150.	1100000111100111		195.	1100110001100111
	151.	1100000111110011		196.	1100110001110011
	152.	1100000111111000		197.	1100110001111000
	153.	1100000111111100		198.	1100110001111100
35	154.	1100001100001111	80	199.	1100110011000011
	155.	1100001100011111		200.	1100110011000111
	156.	1100001100110011		201.	1100110011001100
	157.	1100001100111100		202.	1100110011100011
	158.	1100001110000111		203.	1100110011110000
40	159.	1100001110001111	85	204.	1100110011111000
	160.	1100001110011100		205.	1100111000000111
	161.	1100001111000011		206.	1100111000001111
	162.	1100001111000111		207.	1100111000011100
	163.	1100001111001100		208.	1100111000110011
45	164.	1100001111100011	90	209.	1100111000111000

	210.	1100111000111100		255.	1110001111001100
	211.	1100111001100011		256.	1110001111100000
	212.	1100111001110000		257.	1110011000000111
5	213.	1100111001111000		258.	1110011000001111
	214.	1100111100000011	50	259.	1110011000011100
	215.	1100111100000111		260.	1110011000110011
	216.	1100111100001100		261.	1110011000111000
	217.	1100111100011000		262.	1110011000111100
10	218.	1100111100011100		263.	1110011001100011
	219.	1100111100110000	55	264.	1110011001110000
	220.	1100111100111000		265.	1110011001111000
	221.	1100111110000011		266.	1110011100000011
	222.	1100111110001100		267.	1110011100000111
15	223.	1100111110011000		268.	1110011100001100
	224.	1110000001100111	60	269.	1110011100011000
	225.	1110000001110011		270.	1110011100110000
	226.	1110000001111100		271.	1110011100111000
	227.	1110000011000111		272.	1110011110000011
	228.	1110000011001111		273.	1110011110001100
20	229.	1110000011100011	65	274.	1110011110011000
	230.	1110000011100111		275.	1111000000001111
	231.	1110000011110011		276.	1111000000011111
	232.	1110000011111000		277.	1111000000110011
25	233.	1110000011111100		278.	1111000000111100
	234.	1110000110000111	70	279.	1111000001100011
	235.	1110000110001111		280.	1111000001100111
	236.	1110000110011100		281.	1111000001110011
	237.	1110000111000011		282.	1111000001111000
	238.	1110000111000111		283.	1111000001111100
30	239.	1110000111001100	75	284.	1111000011000011
	240.	1110000111100011		285.	1111000011000111
	241.	1110000111110000		286.	1111000011001100
	242.	1110000111111000		287.	1111000011100011
	243.	1110001100000111		288.	1111000011110000
35	244.	1110001100001111	80	289.	1111000011111000
	245.	1110001100011100		290.	1111000110000011
	246.	1110001100110011		291.	1111000110000111
	247.	1110001100111000		292.	1111000110001100
	248.	1110001100111100		293.	1111000110011000
40	249.	1110001110000011	85	294.	1111000110011100
	250.	1110001110000111		295.	1111000111000011
	251.	1110001110001100		296.	1111000111001100
	252.	1110001110011000		297.	1111000111100000
	253.	1110001110011100		298.	1111001100000011
45	254.	1110001111000011	90	299.	1111001100000111

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310.	1111100000111000
311.	1111100000111100
312.	1111100001100011
313.	1111100001111000
314.	1111100011000011
315.	1111100011001100
316.	1111100110000011
317.	1111100110001100
318.	1111100110011000

5
10
20

[illegible]

Appendix D

Example implementation of 8 bits into 13 bits encoding means as a synthesisable Verilog model.

```

5      `timescale 1ns / 1ps
      module coder_8b13b_fast(
          clock,      // clock reset,      // power up reset
          din,        // Data in
          cin,        // Command in
10         out,        // data output
          encerr);    // encoding error (reserved input)

      input  clock;
      input  reset;    // system reset. Active high
      input  [7:0] din; // msb=7 lsb=0
15     input  cin;      // 1 - Command, 0 - data
      output [12:0] out; // msb=0 lsb=12
      output  encerr;   // 1 = error
      //-----
      // control codes:
20     //-----
      parameter ENC0_IP = 9'h11C;
      parameter ENC1_IP = 9'h13C;
      parameter ENC2_IP = 9'h15C;
      parameter ENC3_IP = 9'h17C;
25     parameter ENC4_IP = 9'h19C;
      parameter ENC5_IP = 9'h1BC;
      parameter ENC6_IP = 9'h1DC;
      parameter ENC7_IP = 9'h1FC;
      parameter ENC8_IP = 9'h1F7;
30     parameter ENC9_IP = 9'h1FB;
      parameter IDLE_IP = 9'h1FD;
      parameter COMM_IP = 9'h1FE;
      parameter ENCA_IP = 9'h1FF;
      parameter ENCB_IP = 9'h1FA; // ??
35     //-----
      // control encoding 11 of 13
      // end bits are both replicated
      //-----
40     parameter ENC0 = 11'b00001110000;
      parameter ENC1 = 11'b11110001111;
      parameter ENC2 = 11'b00011111000;
      parameter ENC3 = 11'b11100000111;
      parameter ENC4 = 11'b00110001100;
      parameter ENC5 = 11'b11001110011;
45     parameter ENC6 = 11'b00111111100;

```

```

parameter ENC7 = 11'b1100000011;
parameter ENC8 = 11'b01100000110;
parameter ENC9 = 11'b10011111001;
parameter IDLE = 11'b01110001110;
5 parameter COMM = 11'b10001110001;
parameter ENCA = 11'b01111111110;
parameter ENCB = 11'b10000000001;
//-----
// internal signals:
10 // registers wires
//-----

reg [08:0] inputlatch; // latch input code
reg [09:0] data, data_i; // latch raw encoding
15 reg [10:0] comm, comm_i; // command/databar
reg [12:0] out; // output encoding
wire [12:0] out_i;
wire [9:0] reflt; // reflected bits
reg encerr, encerr_i; // input error line
20 reg command, command_i; // latched cin
reg invert, invert_i; // invert raw data encoding
reg reflect, reflect_i; // reflect raw data encoding
//-----
// code:
25 //-----
// assign final latch stage

assign out_i = command ? {comm[10],comm[10:0],comm[0]}:
30 invert ? ~{reflt[9],reflt[9:5],1'b0,reflt[4:0],reflt[0]}:
{reflt[9],reflt[9:5],1'b0,reflt[4:0],reflt[0]};

assign reflt = reflect ? {data[00],data[01],data[02],
35 data[03],data[04],data[05],
data[06],data[07],data[08],
data[09]}:
data[9:0];
// assign encoding stage (combinatorial)

always @(inputlatch)
40 begin
if (inputlatch[8])
begin // Command encodings
command_i <= 1'b1;
invert_i <= 1'b0; // not used
45 reflect_i <= 1'b0; // not used

```



```

data_i      <=  IDLE;
case ({inputlatch[8:0]})
  IDLE_IP : begin comm_i <= IDLE; encerr_i <= 1'b0; end
  COMM_IP : begin comm_i <= COMM; encerr_i <= 1'b0; end
  ENC0_IP : begin comm_i <= ENC0; encerr_i <= 1'b0; end
  ENC1_IP : begin comm_i <= ENC1; encerr_i <= 1'b0; end
  ENC2_IP : begin comm_i <= ENC2; encerr_i <= 1'b0; end
  ENC3_IP : begin comm_i <= ENC3; encerr_i <= 1'b0; end
  ENC4_IP : begin comm_i <= ENC4; encerr_i <= 1'b0; end
  ENC5_IP : begin comm_i <= ENC5; encerr_i <= 1'b0; end
  ENC6_IP : begin comm_i <= ENC6; encerr_i <= 1'b0; end
  ENC7_IP : begin comm_i <= ENC7; encerr_i <= 1'b0; end
  ENC8_IP : begin comm_i <= ENC8; encerr_i <= 1'b0; end
  ENC9_IP : begin comm_i <= ENC9; encerr_i <= 1'b0; end
  ENCA_IP : begin comm_i <= ENCA; encerr_i <= 1'b0; end
  ENCB_IP :      begin comm_i <= ENCB; encerr_i <= 1'b0; end

  default : begin comm_i <= IDLE; encerr_i <= 1'b1; end
endcase
else
  begin
    // data encoding note: 5 top bits & 5 bottom
    command_i      <= 1'b0;
    invert_i        <= inputlatch[7];
    reflect_i       <= inputlatch[6];
    comm_i          <= IDLE;
    encerr_i        <= 1'b0;
    case ({inputlatch[5:0]})
      6'h00 : begin data_i <= 10'b0111011111; end
      6'h01 : begin data_i <= 10'b1111011111; end
      6'h02 : begin data_i <= 10'b0111001111; end
      6'h03 : begin data_i <= 10'b0111011110; end
      6'h04 : begin data_i <= 10'b0011001111; end
      6'h05 : begin data_i <= 10'b0011011111; end
      6'h06 : begin data_i <= 10'b0011001110; end
      6'h07 : begin data_i <= 10'b0011011110; end
      6'h08 : begin data_i <= 10'b0011101111; end
      6'h09 : begin data_i <= 10'b0111101111; end
      6'h0A : begin data_i <= 10'b0011101110; end
      6'h0B : begin data_i <= 10'b0011011100; end
      6'h0C : begin data_i <= 10'b0001101111; end
      6'h0D : begin data_i <= 10'b1001101111; end
      6'h0E : begin data_i <= 10'b0001101110; end
      6'h0F : begin data_i <= 10'b0001101100; end
      6'h10 : begin data_i <= 10'b1100011111; end

```

45

```

        6'h3E : begin data_i <= 10'b1000000011; end
        6'h3F : begin data_i <= 10'b1001100011; end
        default : begin data_i <= {10{1'bx}}; end
    endcase
5      end
    end
    //-----
    // clocked process
    //-----
10     always @(posedge clock or posedge reset)      // async reset
    //always @(posedge clock)                        // sync reset
    begin
        if (reset)
        begin
15             inputlatch <= IDLE_IP;      // comma instead of data 0 don't know
                                           // how user interprets data 0
            comm          <= IDLE;
            data          <= IDLE;
            command <= 1'b1;
20             invert <= 1'b0;
            reflect <= 1'b0;
            encerr_i <= 1'b0;
            out <= {IDLE[10],IDLE,IDLE[0]};
            end
        else
        begin
25             inputlatch <= {cin,din};
            comm          <= comm_i;
            data          <= data_i;
30             command <= command_i;
            invert <= invert_i;
            reflect <= reflect_i;
            encerr <= encerr_i;
            out <= out_i;
35             end
        end
    end
endmodule

```

Appendix E

Example implementation of 13 bits into 8 bits decoding means as a synthesisable Verilog model.

```

5  `timescale 1ns / 1ps
   module decoder_8b13b_fast(
       clock,          // clock
       reset,          // power up reset
10      din,           // Data in
       cmd,            // Command out
       out,            // data output
       error;          // error detected output

       input  clock;
       input  reset;    // system reset. Active high
15      input [12:0] din; // msb=0 lsb=12
       output cmd;      // 1 - Command, 0 - data
       output [7:0] out; // msb=7 lsb=0
       output error;    // error detected
       //-----
20      // control codes:
       //-----
       parameter ENC0_OP = 8'h1C;
       parameter ENC1_OP = 8'h3C;
       parameter ENC2_OP = 8'h5C;
25      parameter ENC3_OP = 8'h7C;
       parameter ENC4_OP = 8'h9C;
       parameter ENC5_OP = 8'hBC;
       parameter ENC6_OP = 8'hDC;
       parameter ENC7_OP = 8'hFC;
30      parameter ENC8_OP = 8'hF7;
       parameter ENC9_OP = 8'hFB;
       parameter IDLE_OP = 8'hFD;
       parameter COMM_OP = 8'hFE;
       parameter ENCA_OP = 8'hFF;
35      parameter ENCB_OP = 8'hFA; // ??
       //-----
       // control encoding
       //-----
40      parameter ENC0 = 13'b00000011100000;
       parameter ENC1 = 13'b1111100011111;
       parameter ENC2 = 13'b0000111110000;
       parameter ENC3 = 13'b1111000001111;
       parameter ENC4 = 13'b0001100011000;
45      parameter ENC5 = 13'b1110011100111;
       parameter ENC6 = 13'b0001111111000;

```

```

parameter ENC7 = 13'b111000000111;
parameter ENC8 = 13'b0011000001100;
parameter ENC9 = 13'b1100111110011;
parameter IDLE = 13'b0011100011100;
5 parameter COMM = 13'b1100011100011;
parameter ENCA = 13'b0011111111100;
parameter ENCB = 13'b1100000000011;

//-----
10 // internal signals:
// registers wires
//-----
reg cmd; // output command/databar bit
wire cmd_i;
15 reg cmdl_d,
cmdl; // stage latch command bit
wire cmdl_i;
reg refl, refl_i,
refd; // bits were reflected
20 reg [5:2] pred; // part decode bits
wire [5:2] pred_i;
reg [7:0] out, out_c, // output instruction/data
out_du; // lower decode
wire [7:0] out_i, out_d;
25 reg [12:0] din_latch; // input latch for encoded din
reg [12:0] rfl_latch; // stage latch for reflected encoded din
wire [12:0] rfl_latch_i, rfl_latch_p;
wire cmdt_i,
errt_i;
30 reg [12:0] stg_latch;
reg [12:0] stg_latch_i; // stage latch
reg errl, errl_i,
errl_d;
35 reg error;
wire error_i;
integer i;
//-----
// code:
//-----
40 // invert data into rfl_latch ready for reflection, rfl_latch[6] holds sense
assign rfl_latch_i = cmdl_i | ~din_latch[6] ? din_latch :
{~din_latch[12:7], 1'b1, ~din_latch[5:0]};
assign rfl_latch_p = rfl_latch;
// all commands are mirrors
45 assign cmdl_i = (~|(din_latch[11:7]^(din_latch[1],din_latch[2],

```

```

        din_latch[3],din_latch[4],din_latch[5]))&&
        ((&din_latch[7:5])|(~|din_latch[7:5]));
// simple error detect, bits must have a partner
always @(din_latch)
5   begin
        errl_i <= 1'b0;
        for(i=1;i<12;i=i+1)
            begin
10              if((din_latch[i] != din_latch[i-1]) && (din_latch[i] != din_latch[i+1]))
                  begin
                        errl_i <= 1'b1;
                    end
                end
            if((din_latch[12] != din_latch[11]) || (din_latch[1] != din_latch[0]))
15              begin
                        errl_i <= 1'b1;
                    end
                // simple error detect, 16 bit sequence maximum
                casex(din_latch)
20                  14'b1_??????_?_?????? : errl_i <= 1'b1;
                  14'b?_000000_?_00???? : errl_i <= 1'b1;
                  14'b?_111111_?_11???? : errl_i <= 1'b1;
                  14'b?_????00_?_000000 : errl_i <= 1'b1;
                  14'b?_????11_?_111111 : errl_i <= 1'b1;
25              endcase
            end
            // reflect encoding for smaller table lookup
            // bit 13 remembers original encoding for msb-1 of output (out)
            always @(rfl_latch_p or cmdl)
30            //always @(rfl_latch_p or cmdt_i)
            begin
                if((rfl_latch_p[11:7]>{rfl_latch_p[1],rfl_latch_p[2],rfl_latch_p[3],
                    rfl_latch_p[4],rfl_latch_p[5]})&&!cmdl)
                    begin
35                        stg_latch_i <= {rfl_latch_p[0],rfl_latch_p[1],rfl_latch_p[2],rfl_latch_p[3],rfl_latch_p[4],
                            rfl_latch_p[5],rfl_latch_p[6],rfl_latch_p[7],rfl_latch_p[8],rfl_latch_p[9],
                                rfl_latch_p[10],rfl_latch_p[11],rfl_latch_p[12]};
                        refl_i <= 1'b1;
                    end
                else
40                begin
                        stg_latch_i <= rfl_latch_p;          refl_i <= 1'b0;
                    end
                end
45            end

```

```

// overdrive command bit if error has been found
assign cmd_i = cmdl_d | errl_d;

assign out_i = errl_d ? IDLE_OP:
5      cmdl_d ? out_c:
      out_d[7:0];
assign error_i = errl_d;
// see if longest terms ar at front or rear
// assign encoding (combinatorial)
10 always @(stg_latch or
      cmdl_d or
      refl)
begin
    // code lookup for command
15    case ({stg_latch[12:0]})
        IDLE : begin out_c <= IDLE_OP; end
        COMM : begin out_c <= COMM_OP; end
        ENC0 : begin out_c <= ENC0_OP; end
        ENC1 : begin out_c <= ENC1_OP; end
20        ENC2 : begin out_c <= ENC2_OP; end
        ENC3 : begin out_c <= ENC3_OP; end
        ENC4 : begin out_c <= ENC4_OP; end
        ENC5 : begin out_c <= ENC5_OP; end
        ENC6 : begin out_c <= ENC6_OP; end
25        ENC7 : begin out_c <= ENC7_OP; end
        ENC8 : begin out_c <= ENC8_OP; end
        ENC9 : begin out_c <= ENC9_OP; end
        ENCA : begin out_c <= ENCA_OP; end
        ENCB : begin out_c <= ENCB_OP; end
30        default : begin out_c <= IDLE_OP; end
    endcase
end
assign out_d[7] = stg_latch[6]; // set msb = encode bit 6
assign out_d[6] = refl; // set msb-1 = reflection
35 assign out_d[5] =!(stg_latch[4] & stg_latch[3]);
assign out_d[4] =!((stg_latch[8] & stg_latch[4] & stg_latch[3]) |
      (stg_latch[9] & stg_latch[8]));
assign out_d[3] =!((stg_latch[8] & stg_latch[4] & stg_latch[3] &
40      !stg_latch[7] & stg_latch[2]))
      (stg_latch[4] & stg_latch[3] & stg_latch[10] & !stg_latch[8])|
      (!stg_latch[4] & stg_latch[3]) & stg_latch[9] & stg_latch[2] & stg_latch[11])|
      (!stg_latch[4] & stg_latch[3]) & !stg_latch[9] & stg_latch[8]) &
      stg_latch[1] & !stg_latch[11]));
assign out_d[2] =!(!stg_latch[10] & stg_latch[2] & !stg_latch[7]) &
45      !stg_latch[7] & stg_latch[9]) & !stg_latch[9] &

```



```

begin
  if (reset)
    begin
      din_latch    <=    IDLE;
      rfl_latch    <=    IDLE;
      stg_latch    <=    IDLE;
      out          <=    IDLE_OP;
      cmdl         <=    1'b1;
      cmdl_d       <=    1'b1;
    end
  else
    begin
      errl         <= 1'b0;
      errl_d       <= 1'b0;
      refl         <= 1'b0;
      cmd          <= 1'b1;
      error        <= 1'b0;
      pred         <= 4'b0;
    end
  end
  begin
    din_latch    <=    din;
    rfl_latch    <=    rfl_latch_i;
    stg_latch    <=    stg_latch_i;
    out          <=    out_i;
    cmdl         <=    cmdl_i;
    cmdl_d       <=    cmdl;
    errl         <=    errl_i;
    errl_d       <=    errl;
    refl         <=    refl_i;
    cmd          <=    cmd_i;
    error        <=    error_i;
    pred         <=    pred_i;
  end
end
endmodule

```